International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V70I1P232

Volume 70 Issue 1, 275-282, January, 2022

# Operability of Skidding Tracks Using Various Strengthening Methods

Vladimir Valentinovich Nikitin[1], Vyacheslav Gennadievich Kozlov[2], Vladimir Anatolyevich Zelikov[3], Andrey Nikolaevich Bryukhovetsky[4], Alexey Alekseevich Skrypnikov[5], Albert Masugutovich Burgonutdinov[6], Dmitry Mikhailovich Levushkin[7], Vadim Alexandrovich Timofeev[8]

[1,7]*Mytishchi Branch of Bauman Moscow State Technical University (National Research University), Mytischi, Russia*

[2]*Voronezh State Agrarian University named after Emperor Peter the Great, Voronezh, Russia*
[3]*Voronezh State Forest Engineering University named after G. F. Morozov, Voronezh, Russia*

[4,5,8]*Voronezh State University of Engineering Technologies, Voronezh, Russia*

[6]*Perm National Research Polytechnic University, Perm, Russia*

***Abstract*** *— The experimental determination of the operability of trunk lines, as well as the functional dependence of the increase in the depth of the track on the number of vehicle passages, considering the physical and mechanical properties of forest soils, especially during the autumn-spring impassability, is important for the development of measures to reduce the seasonality of forest transport. The aim of the work is an experimental study of the full drivability of the trunk lines for tracked and wheeled tractors in muddy season, as well as testing the method of determining the optimal distance between logging roads to accommodate the road network of the raw material base. Analysis of statistical processing of experimental research results has shown that all series, as a rule, correspond to the normal distribution law, which is determined by the ratio of symmetry and kurtosis indicators to their average errors. Comparative tests of tracked and wheeled tractors when moving along a reinforced track have shown that a reinforced track, when moving a wheeled tractor, can withstand a significantly greater number of passes than when moving a tracked tractor. Tests have shown that a wheeled tractor, when moving at a speed of 8.6 km/h with a bundle of 3 $m^3$, can carry out 200 passes after repair.*

**Keywords —** *Strengthening method, depth of the track, sealing, movers.*

## I. INTRODUCTION

When placing a network of paths according to the scheme of apiary and trunk lines – branches – mainline road, it is of particular importance to study the issue of the operability of primary forest transport routes, especially the study of the requirements for the strength of trunk lines [1-10].

The latter makes it necessary to take into account the soil conditions of the terrain when establishing the optimal distance between long-term operability roads.

When considering the issue of placing a forest transport network and establishing the optimal distance between logging roads on a specific terrain model, the calculated values of some indicators were taken as a basis.

One of the main conditions observed in the preparation of the research methodology was to ensure the same conditions for conducting the experiment. In this regard, a circular arrangement pattern of the measurement forest plots was adopted [11]-[14].

## II. METHODS

According to the scheme, tractors were moved along a ring, on which 25-meter long various metering sections were located sequentially with some interval, respectively: an unreinforced portage –1; reinforced postage – 2; and a reinforced track of a failed portage – 3. Each ring was intended for one-way movement of the tractor only with a regular load. To ensure relatively homogeneous ground conditions, the ring tracks were located close to each other (Figures 1 and 2).

During the first trips along the portage at the forest cutover patch of the second series of experiments was characterized by a large number of stumps up to 600 mm high and felling residues; (when the tractor was moving without a load), it was revealed that the value of the variation coefficient *v* for different points ranged quite widely from 2 to 12% [15, 16]. Therefore, setting the accuracy rate of p=5% and taking the variation coefficient v=12%, the minimal number of required observations (points) was determined by the formula:

$$n = \frac{V^2 t^2}{p^2} = \frac{12^2 \cdot 1.3^2}{5^2} \cong 10 \qquad (1)$$

where t is the probability of observations, determined by the Laplace integral (since the experiments were conducted in the field, it was assumed that t = 1.3, which corresponds to 80% of the observation probability).

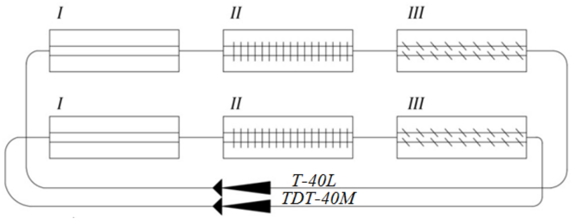

**Fig. 1. A ring diagram of the measurement sections location**

During the tests, the depth of the track and the deformability of the soil were measured on each metering section in five cross-sections, in both tracks (10 points). Besides, the weight water content and volumetric weight of the soil skeleton at the bottom of the track were determined by an accelerated method using a density and moisture meter of the N.P. Kovalev system [17].

The diagram of metering the depth of the track is shown in Figure 2.

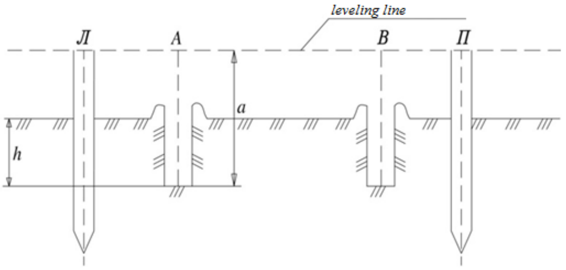

**Fig. 2. Diagram of conducting depth measurements in cross-sections *h* is the depth of the track without considering the rollers of side bulging, and *a* is the depth of the track relative to the levelling line**

The cut-over lands and meadow ground were distinguished by undisturbed ground-soil structure and flat terrain. Forest cutover patch from the first series of the experiment was characterized by a large number of stumps up to 1,400 mm high, two-year-old undergrowth mainly of hardwoods; the thickness of the vegetation layer was about 250 mm with the presence of a root system covering a loam layer. The nature of the ground and soil distribution over the depth was heterogeneous. In some places of the portage, there was a peat layer with a thickness exceeding the ground clearance of the tractor. The meadow ground was characterized by the presence of a vegetation layer of a small thickness of about 20 mm, with an underlying loam layer. The forest cutover patch of the second series of experiments was characterized by a large number of stumps up to 600 mm high and felling residues; the nature of the ground and soil distribution over the depth was heterogeneous; the thickness of the vegetation layer was about 60-160 mm, a layer of sandy loam was below to a depth of 300 mm from the ground surface, followed by heavy loam.

Light wheeled tractors were used in experiments as vehicles [18].

Technological loads (bundles of branches) amounted to 1.75, 2.25, and 3 m$^3$. The transportation of bundles in a semi-loaded position was carried out with butt-end-first. Before the experiment, four bundles of trees were prepared and weighed.

In the course of the experiment, the movement of tractors along an unreinforced portage continued until the appearance of intense slippage of the wheeled vehicle, which was accepted as a criterion for the portage destruction. Movement along the portage, reinforced by felling remnants (branches), was carried out until the destruction of the reinforcement and the beginning of the track formation, and movement along the newly reinforced track of the failed portage – until the destruction of the reinforcement and the appearance of intense slippage of the mover.

As the tests show, the movement along the track was accompanied by a noticeable wheel slippage only in those places where tree roots were strongly developed. Portage sections located close to the stumps were the most impassable.

In parallel with the wheeled tractor, multiple passes along the track were carried out by a tracked tractor.

During the tests, some fundamental differences were revealed in the track formation process during the movement of wheeled and tracked tractors. Thus, the destruction of the grass-covered layer was much more intense when the caterpillar tractor was moving. It was also characteristic that the caterpillar tractor had no noticeable lateral bulging of the waterlogged soil from the track.

The distinctive features of the track formed by tracked and wheeled tractors are visible when comparing:

1) the track formed by the wheeled tractor is characterized by the presence of rollers of lateral bulging of the soil;

2) due to lateral bulging, the content of the soil in the track in plastic and fluid states is insignificant;

3) the track, formed by a caterpillar tractor, is characterized by a significant content of the soil in its being in plastic and fluid states.

The root system of neighbouring stumps, available on the portage, improved movement conditions of the caterpillar tractor on the wheel track.

According to the accepted methodology, metering portages were selected and prepared, on which metering cross-sections were marked with pegs (Figure 2). The reference level required for metering the track depth was established by ground levelling. The corresponding data on the track depth are given in Tables 1-6. During the experiment, the wheeled tractor moved at 1st gear (with speed up to 6.1 km/h) without locking the wheels, while the caterpillar tractor moved at 3rd gear.

In the first series of experiments, when driving a tractor with a bundle of trees of 3 m$^3$, 34 passes were performed. The high moisture of the upper layer of the soil, corresponding to its fluid consistency, determined the fact that already at the first pass, almost along the entire length of the metering area, a rupture of the vegetation layer was observed. As a result, the depth of the wheel track increased intensively during subsequent passes of the tractor. This process continued until the tractor wheels reached the dense bulk of real soil (Table 7). After 34 passes, the tests of portage had to be stopped due to the inability to overcome the root threshold and the threat of loss of transverse stability of the tractor.

In the second series of experiments, the tractor was moving with a load of 2.25 m$^3$ and completed 80 passes. On this portage, a confident movement of the tractor was observed up to the 13th pass. On the 13th pass, the tractor failed to gain traction at the second cross-section near the larger stump. After 48/50 passes, intense wheel slippage was observed. After completing 80 passes, the tests were stopped for the same reason as in the first experiment with a load of 3 m$^3$.

In the third series of experiments with a bundle of trees of 1.75 m$^3$, only 40 passes were performed. The tests were discontinued due to the failure of the portage (in the intermediate zone, the track depth exceeded the ground clearance of the tractor).

In the fourth experiment, when moving a caterpillar tractor with a bundle of spruce wood, a total of 50 passes were performed (driving only at the 3rd gear). On the 39th pass, the bottom of the tractor touched the surface of the portage. At the 47th pass, the tractor engine began to stall, and at the 49th pass, the tractor driver had to switch from the 3rd to 2nd gear. After 50 passes, the tests on this portage were stopped.

Experimental studies of the increase in the depth of the track depending on the number of passes during the movement of a wheeled tractor without a load were carried out at the forest cutover patch in the first (autumn) test series. In this test, due to the very high soil moisture, the tractor performed only 40 passes. After 40 passes of the tractor, the track depth on the heaviest sections of the portage reached about 500 mm. In areas where the thickness of the humus layer was insignificant, after 25-30 passes, the wheel track formed less intensively.

**Table 1. The 1st Series of Experiments**

| Forest cutover patch; Tractor T-40L, Q=3.05 m$^3$ | | | | |
|---|---|---|---|---|
| Number of tractor passes, n | Average track depth (H$_{av}$), mm | Relativesoilmoisture (W$_{rel}$) | Volumetric mass ($\gamma_c$), g/cm$^3$ | Number of blows by the drummer of the Road Research Institute, N |
| 0 | 0 | 2.75 | 1.16 | 1 |
| 10 | 176 | 2.06 | 1.16 | 1 |
| 20 | 259 | 1.11 | 1.72 | 3 |
| 30 | 310 | 0.70 | 1.83 | 4 |
| 34 | 336 | 0.61 | 1.85 | 4 |

In this series of experiments, studies were also conducted on the increase in the depth of the track depending on the number of passes when a wheeled tractor moved through a forest meadow. In the forest meadow, the experiments were carried out when moving both without a load (experiment No. 6) and with a load of 1.6 m$^3$ (experiment No. 7).

According to the used method, during the entire study of the track formation intensity, the weight moisture (w%) and the deformability of the track surface were determined depending on the number of drummer strokes (N). To determine the moisture, the volumetric mass of wet soil ($\gamma_{vol}$) and the volumetric mass of the skeleton ($\gamma_s$) were measured using a density and moisture meter of the N.P. Kovalev system.

**Table 2. The 2nd Series of Experiments**

| Forest cutover patch; Tractor T-40L, Q=2.25 m$^3$ | | | | |
|---|---|---|---|---|
| Number of tractor passes, n | Average track depth (H$_{av}$), mm | Relativesoilmoisture (W$_{rel}$) | Volumetric mass ($\gamma_c$), g/cm$^3$ | Number of blows by the drummer of the Road Research Institute, N |
| 0 | 0 | 2.41 | 1.36 | 1 |
| 10 | 200 | 1.43 | 1.52 | 2 |
| 20 | 232 | 0.76 | 1.82 | 4 |
| 30 | 274 | 0.69 | 1.85 | 4 |
| 40 | 307 | 0.68 | 1.83 | 4 |
| 50 | 342 | 0.76 | 1.86 | 4 |
| 60 | 367 | 0.66 | 1.91 | 5 |
| 70 | 384 | 0.65 | 1.86 | 5 |
| 80 | 392 | 0.61 | 1.90 | 5 |

Based on experimental data, certain values of track depth (H$_{av}$), relative humidity (W$_{rel}$), density ($\gamma_c$), and the number of impacts (N) were obtained depending on the number of passes (n). These values are given in Tables 1-4 (spring series of the experiments) and 5-7 (autumn series of the experiments).

Analyzing Tables 1-7, the following features of track formation intensity during the movement of light wheeled and a caterpillar tractor can be noted:

1) the root system of stumps, located close to the track worsens the transverse stability of wheeled tractors, as evidenced by the insignificant number of passes in experiments of the 1st and 5thseries;

2) the absence of stumps close to the track allowed increasing the number of passes to 80 in the experiments of the 2nd series;

3) comparing the data, obtained in the 1st, 2nd, 3rd, and 5th series of experiments with the data of the 5th series shows that with an increase in the depth of the track, the soil moisture at the bottom of the track decreases. It was also noted that the soil moisture at the bottom of the track, formed by a wheeled tractor, is less than the soil moisture during the movement of a caterpillar tractor due to the more intense displacement of waterlogged soil from the track by a wheeled tractor;

4) at the same specific loads of tracked and wheeled tractors, the depth of the track formed by the wheeled tractor is less than the depth of the track formed by the tracked tractor. So, at 50 passes and loads, equal, respectively, to 3.0 m$^3$ for a caterpillar tractor and 2.25 m$^3$ for a wheeled tractor, i.e. at the same specific load of 0.5 m$^3$/t, the track depth for a wheeled tractor was 342 mm, while for a tracked one – 420 mm;

5) comparing the experiments of 5th and 6th series shows that at the same impact, the depth of the track at the forest

cutover patch of the second series of experiments was characterized by a large number of stumps up to 600 mm high and felling residues; (experiment No. 5) increases significantly more intensively comparing with the formation of a track on a forest meadow (experiment No. 6), which is explained by lower moisture and higher density, and thereby, increased bearing capacity of the soil and subsoil at a forest meadow in comparison with forest cutover patch. Comparing the results of experiments of the 5th and 6th series with results of the 1st and 2nd series, it can be noted that when changing the load on the tractor wheel from 1815 kgf at $Q_{full}$= 2.5-3.0 m$^3$ to 1175 kgs, corresponding to moving the tractor without load, causes a decrease in the pDe index from 53.3 to 39.9 kgf/cm.

$$h = \alpha_1 + \alpha_2 n + \alpha_3 lnn \tag{2}$$

**Table 3. The 3rd Series of Experiments**

| Forest cutover patch; Tractor T-40L, Q=1.75 m$^3$ | | | | |
|---|---|---|---|---|
| Number of tractor passes, n | Average track depth ($H_{av}$), mm | Relativesoilmoisture ($W_{rel}$) | Volumetric mass ($\gamma_c$), g/cm$^3$ | Number of blows by the drummer of the Road Research Institute, N |
| 0 | 0 | 2.58 | 1.34 | 1 |
| 10 | 140 | 0.80 | 1.68 | 1 |
| 20 | 235 | 0.72 | 1.89 | 5 |
| 30 | 270 | 0.82 | 1.79 | 5 |
| 40 | 313 | 0.67 | 1.89 | 8 |

**Table 4. The 4th Series of Experiments**

| Forest cutover patch; Tractor T-40L, Q=3.0 m$^3$ | | | | |
|---|---|---|---|---|
| Number of tractor passes, n | Average track depth ($H_{av}$), mm | Relativesoilmoisture ($W_{rel}$) | Volumetric mass ($\gamma_c$), g/cm$^3$ | Number of blows by the drummer of the Road Research Institute, N |
| 0 | 0 | 3.04 | 1.35 | 1 |
| 10 | 246 | 1.3 | 1.67 | 4 |
| 20 | 297 | 1.0 | 1.78 | 8 |
| 30 | 351 | 0.99 | 1.80 | 8 |
| 40 | 389 | 0.89 | 1.80 | 8 |
| 50 | 420 | 0.77 | 1.85 | 9 |

**Table 5. The 5th Series of Experiments**

| Forest cutover patch; Tractor T-40L, Q=0 | | | | |
|---|---|---|---|---|
| Number of tractor passes, n | Average track depth ($H_{av}$), mm | Relativesoilmoisture ($W_{rel}$) | Volumetric mass ($\gamma_c$), g/cm$^3$ | Number of blows by the drummer of the Road Research Institute, N |
| 1 | 41.2 | - | - | 1 |
| 10 | 190.2 | 2.80 | 1.10 | 2 |
| 20 | 243.7 | 2.65 | 1.17 | 2 |
| 30 | 291.4 | 2.09 | 1.32 | 2 |
| 40 | 343.3 | 1.35 | 1.45 | 2 |

**Table 6. The 6th Series of Experiments**

| Forest meadow; Tractor T-40L, Q=0 | | | | |
|---|---|---|---|---|
| Number of tractor passes, n | Average track depth ($H_{av}$), mm | Relativesoilmoisture ($W_{rel}$) | Volumetric mass ($\gamma_c$), g/cm$^3$ | Number of blows by the drummer of the Road Research Institute, N |
| 1 | 19.7 | - | - | 3 |
| 10 | 40.9 | 2.41 | 1.22 | 4 |
| 30 | 83.2 | 2.16 | 1.33 | 5 |
| 130 | 167.1 | 1.57 | 1.48 | 9 |

**Table 7. The 7th Series of Experiments**

| Forest meadow; Tractor T-40L, Q=1.6 m$^3$ | | | | |
|---|---|---|---|---|
| Number of tractor passes, n | Average track depth ($H_{av}$), mm | Relativesoilmoisture ($W_{rel}$) | Volumetric mass ($\gamma_c$), g/cm$^3$ | Number of blows by the drummer of the Road Research Institute, N |
| 1 | 20.3 | - | - | |
| 10 | 131.6 | 2.20 | 1.39 | |
| 30 | 195.6 | 1.34 | 1.48 | |
| 60 | 248.9 | 1.02 | 1.56 | |

For a given Q, the functions *ψ<sub></sub>*$\psi_i(Q)$ take constant values. For a given value of Q, i.e. for a given series of experiments, we define $\psi_i(Q)$ using the least-squares method.

Let us define $\alpha_i$ from the condition for a minimum of the expression:

$$\text{У} = \sum_{j=1}^{s}(h-h_j)^2 = min \quad (3)$$

that is, it is necessary to solve the system of equations:

$$\frac{\sigma \text{У}}{\sigma\alpha_1} = \frac{\sigma \text{У}}{\sigma\alpha_2} = \frac{\sigma \text{У}}{\sigma\alpha_3} = min \quad (4)$$

$$\sum_{j=1}^{s}(\alpha_1+\alpha_2 n_j+\alpha_3 lnn_j)=0 \quad (5)$$

$$\sum_{j=1}^{s}(\alpha_1+\alpha_2 n_j+\alpha_3 lnn_j)n_j=0 \quad (6)$$

$$\sum_{j=1}^{s}(\alpha_1+\alpha_2 n_j+\alpha_3 lnn_j)lnn_j=0 \quad (7)$$

where: j=1,2,3......,s is the number of measurements in the experimental series.

After simplifying the systems, we get the equations of the form:

$$\alpha_1 s+\alpha_2\sum_{j=1}^{s} n_j+\alpha_3\sum_{j=1}^{s} lnn_j = \alpha_2\sum_{j=1}^{s} h_j (8)$$

$$\alpha_1\sum_{j=1}^{s} n_j+\alpha_2\sum_{j=1}^{s}(n_j)^2+ \alpha_3\sum_{j=1}^{s} n_j lnn_j = \sum_{j=1}^{s} n_j h_j (9)$$

$$\alpha_1\sum_{j=1}^{s} lnn_j+\alpha_2\sum_{j=1}^{s} n_j lnn_j+ \alpha_3\sum_{j=1}^{s}(lnn_j)^2 = \sum_{j=1}^{s} h_j ln\, n_j (10)$$

To calculate the coefficients of the left part of the system (10), it is enough to calculate the expressions for the sum:

$$N = \sum_{j=1}^{s}(lnn_j)^2 \quad (11)$$

$$N_2 = \sum_{j=1}^{s} lnn_j; \quad (12)$$

$$N_3 = \sum_{j=1}^{s}(n_j)^2; \quad (13)$$

$$N_4 = \sum_{j=1}^{s} n_j lnn_j; \quad (14)$$

$$N_5 = \sum_{j=1}^{s}(lnn_j)^2 \quad (15)$$

In this case, the system (10) can be written in the form:

$$\alpha_1 s+\alpha_2 N_1+\alpha_3 N_3 = \sum h_i = b_1 \quad (16)$$

$$\alpha_1 N_1+\alpha_2 N_3+\alpha_3 N_4=\sum n_j h_i = b_2 \quad (17)$$

$$\alpha_1 N_2+\alpha_2 N_4+\alpha_3 N_5 = \sum h_i lnn_j = b_3 (18)$$

The values of these coefficients obtained as a result of the mathematical processing of experimental data are summarized in Table 8. For experiments of series 1-7, the values of the coefficients were calculated using a similar technique because $W_{rel} > 0.75$.

**Table 8. Coefficient Values**

| $\alpha_i$ | No of experimental series | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| $\alpha_1$ | 48.6 | 38.0 | 40.4 | 99.3 | 77.5 | 33.5 | 26.9 |
| $\alpha_2$ | 10.97 | 1.2 | 7.56 | 7.38 | 7.14 | 1.12 | 6.58 |
| $\alpha_3$ | - | 59.0 | - | - | - | - | - |

One of the main factors affecting the track formation intensity is the moisture content of the soil. The decrease in moisture with the depth of the track is explained by the presence and equilibrium state of moisture, normal for forest soils, according to which the upper vegetation layer represents a dampness zone with a predominance of the capillary moisture coming from above (precipitation and snowmelt). The moisture of this layer gradually decreases with depth, and the wetness zone converts into the zone predominating by film water. The moisture of this zone is minimal. In the presence of groundwater, close to the ground surface, the concerned zone may have a limited thickness or be absent at all. In the general case, below this zone, there is a zone of incomplete capillary saturation, followed by a zone of full capillary saturation directly adjacent to the groundwater level. Considering the above schemes, the functional dependence $W = f(h)$ can be expressed by an equation of the form:

$$W = ah^2 + bh + W_0 \ \% \quad (19)$$

where: W is the soil moisture along with the depth, %; $W_0$is soil moisture on its surface (before starting tests), %; h is the track depth, mm; a, b are coefficients that take into account the heterogeneity of the physical and mechanical properties of the soil along with the depth.

For this series of experiments, the values of a, b, and$W_0$ are determined by the least-squares method, i.e. from the condition of the minimum of the following expression

$$\text{У} = \sum_{j=1}^{s}(w-w_j)^2 = min \quad (20)$$

Then, the desired parameters can be calculated by the formulas:

$$\text{a} = \frac{\text{T}_1(N_1N_3-N_2^2)+\text{T}_2(N_1N_2-SN_3)+\text{T}_3(SN_2-N_1^2)}{2N_1N_2N_3+S(N_2N_4-N_3^2)-N_2^3-N_1^2N_4} = 0.000468(21)$$

$$\text{b}=\frac{\text{T}_1(N_1N_3-N_1N_4)+\text{T}_2(SN_4-N_2^2)+\text{T}_3(N_1N_2-SN_3)}{2N_1N_2N_3+S(N_2N_4-N_3^2)-N_2^3-N_1^2N_4} = -0.32817 \quad (22)$$

$$W_0 = \frac{\text{T}_1(N_2N_4-N_3^2)+\text{T}_2(N_2N_3-N_1N_4)+\text{T}_3(N_1N_3-N_3^2)}{2N_1N_2N_3+S(N_2N_4-N_3^2)-N_2^3-N_1^2N_4} = 72.4 \ (23)$$

where: $N_1 = \sum_{j=1}^{s} h_j;\ N_2 = \sum_{j=1}^{s}(h_j)^2;\ N_3 = \sum_{j=1}^{s}(h_j)^3;\ N_4 = \sum_{j=1}^{s}(h_j)^4;$

$$\text{T}_1 = \sum_{j=1}^{s} W_j;\ \text{T}_2 = \sum_{j=1}^{s} W_j h_j; \text{T}_3 = \sum_{j=1}^{s} W_j (h_j)^2;$$

Employing the above, formula (19) takes the final form:

$$\text{W}=0.000468h^2\text{- }0.32817\text{h}+72.4 \quad (24)$$

The dependence $W = f(h)C$alculated by the formula (24); is shown in Table 9.

**Table 9. Results of Calculating the Dependence $W = f(h)$**

| h (mm) | 0 | 100 | 200 | 300 | 400 |
|---|---|---|---|---|---|
| W,% | 72.4 | 44.3 | 25.4 | 16.0 | 15.9 |

Consider the problem of obtaining the correlation dependence $h = f(n, W)$. For this, for the 2nd series of experiments, we use the expression of the form:

$$h = \varphi_1 + \varphi_2 n + \varphi_3 lnn + (\varphi_4 + \varphi_5 n+\varphi_6 lnn)w \ (25)$$

Coefficients $\varphi_i$can be determined by the least-square method and minimizing the expression:

$$\text{У} = \sum_{j=1}^{s}\sum_{k=1}^{\text{p}}(h-h_{kj})^2 = min \quad (26)$$

i.e. we need to solve the system of equations:

$$\frac{\sigma y}{\sigma\varphi_1} = \frac{\sigma y}{\sigma\varphi_2} = \frac{\sigma y}{\sigma\varphi_3} = \frac{\sigma y}{\sigma\varphi_4} = \frac{\sigma y}{\sigma\varphi_5} = \frac{\sigma y}{\sigma\varphi_6} = 0 \quad (27)$$

where: j=1,2,3........, S is the number of series of experiments; k=1,2,3.....,p is the number of experimental points.

As a result of calculations, based on the data of the 2nd series of experiments, the following coefficient values were obtained: $\varphi_1 = 51.86;\ \varphi_2 = -0.301;\ \varphi_3 = 100.5; \varphi_4 = -0.03;\ \varphi_5 = 0.004;\ \varphi_6 = -1.2$

The dependence $W = f(h)$is obtained by substituting the right part of the equation into the formula (5.51) instead of h. In this case, formula (24) can be written as:

$$W = a(\alpha_1 + \alpha_2 n + \alpha_3 lnn)^2 + b(\alpha_1 + \alpha_2 n + \alpha_3 lnn) + W_0 \quad (28)$$

By replacing the values of the coefficients $a, b, W_0, \alpha_i$we finally get

$$W=60.605332-0.351124n+0.00067392n^2+0.0662688nlnl-17.263518lnn+1.639108(lnn)^2 \quad (29)$$

The functional dependencies $W = f(h)$ , $h = f(h)$ , $W = f(n)$ and $h = f(n, W)$are shown in Figure 3 (based on the data of the 2nd series of experiments).

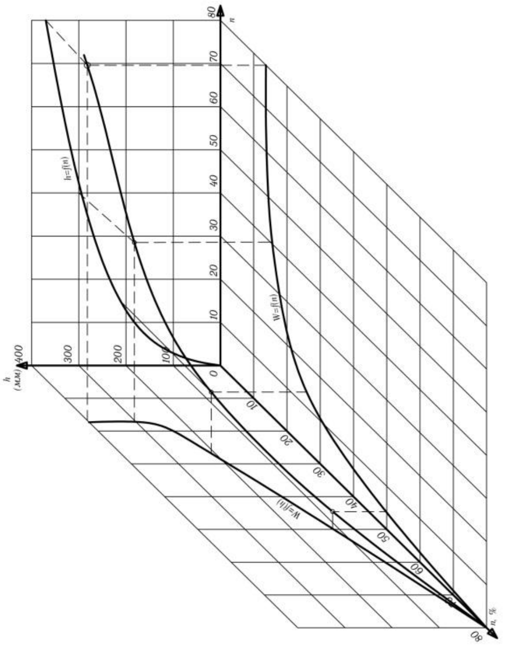

**Fig. 3.Functional dependencies $W = f(h)$, $h = f(h)$, $W = f(n)$, and $h = f(n, W)$**

For the statistical estimate of the conducted experiments, it is necessary to determine what errors can be caused by replacing the parameter with its point estimate and with what level of confidence it can be expected that these errors will not go beyond certain limits. In our case, with a relatively small number of observations, such an assessment is especially relevant. Let us construct a series of confidence limits $I_\beta$, corresponding to the confidence probability $\beta$ for the obtained parameter values. When solving the problem, we will take advantage of the fact that the obtained parameters are expressed in terms of the sum of $K$ independent identically distributed random variables $h_n A$nd that according to the central limit theorem, with the growth of $K$, its distribution law approaches normal.

We will look for a value $\varepsilon_\beta$ for which

$$\mathrm{p}(|\bar{h} - h| < \varepsilon_\beta = \beta \quad (30)$$

Based on the known relationship $p(|x - h| < l) = \Phi\left(\frac{l}{\sigma\sqrt{2}}\right)$we obtain:

$$\mathrm{p}(|\bar{h} - h| < \varepsilon_\beta = \Phi(\frac{\varepsilon_\beta}{\sigma_{\bar{h}}\sqrt{2}}) \quad (31)$$

where $\sigma_{\bar{h}}$are standard deviations of $\bar{h}$.

Comparing the left parts of the above equations, we find:

$$\varepsilon_\beta = \sigma_{\bar{h}}\sqrt{2}\Phi^{-1}(\beta) \quad (32)$$

If taking $\sigma_{\bar{h}}$ as the approximate value of σ, then the problem of constructing confidence limits is solved:

$$I_\beta = (\bar{h} - \varepsilon_\beta, \bar{h} + \varepsilon_\beta) \quad (33)$$

where: $\varepsilon_\beta$ It is determined by the formula (32).

The confidence limits for the considered case are given in Table 10.

**Table 10. Confidence Limits $I_\beta = 137 \pm \varepsilon_\beta$**

| $\beta, \%$ | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\varepsilon_\beta$ | 37 | 37.8 | 38.65 | 39.6 | 40.5 | 41.5 | 42.6 | 43.7 | 44.85 | 46.02 | 47.45 |

Similarly, we find confidence limits for

$$I'_\beta = \sqrt{\breve{D} \pm \varepsilon'_\beta}, \text{ where } \varepsilon'_\beta = \sigma_{\breve{D}}\sqrt{2}\Phi^{-1}(\beta), \quad (34)$$

where, in turn

$$\sigma_D = \sqrt{D(\breve{D})} = \sqrt{\frac{1}{k}\mu_4 - \frac{k-3}{k(k-1)}\breve{D}} \quad (35)$$

where $\mu_4$ is the 4th central moment of the random variable under consideration.

Observations of track formation intensity make it possible to take the normal distribution law as a basis. In this case, $\mu_4 - 3\breve{D}$and then we get

$$I'_\beta = \sqrt{\breve{D} \pm \sqrt{\frac{2}{k-1}D\sqrt{2}\widetilde{\Phi^{-1}}(\beta)}} \quad (36)$$

For the convenience of calculations, we can express $\frac{\varepsilon'_\beta}{\breve{D}}$in terms of $\varepsilon_\beta$. Doing so, we get:

$$\varepsilon'_\beta = \sqrt{\frac{2}{k-1}}\breve{D}\sqrt{2}\Phi^{-1}(\beta) = \frac{1}{\sigma_{\bar{h}}}\sqrt{\frac{2}{k-1}}\breve{D}\varepsilon_\beta \quad (37)$$

from where

$$\frac{\varepsilon'_\beta}{\breve{D}} = \frac{1}{\sigma_{\bar{h}}}\sqrt{\frac{2}{k-1}}\varepsilon_\beta \quad (38)$$

and hence

$$I'_\beta = \sigma_{\bar{h}}\sqrt{1 \pm \frac{2}{\sqrt{k-1}}\Phi^{-1}(\beta)} = \sigma_{\bar{h}}\sqrt{1 \pm \frac{\varepsilon'_\beta}{\breve{D}}} = 28.83\sqrt{1 \pm \frac{\varepsilon'_\beta}{\breve{D}}} \quad (39)$$

After performing calculations using the formula (39), we obtain:

| $\beta, \%$ | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\frac{\varepsilon'_\beta}{\breve{D}}$ | 0.604 | 0.617 | 0.632 | 0.647 | 0.662 | 0.678 | 0.695 | 0.713 | 0.7325 | 0.752 | 0.775 |

Thus, the conducted experiments are characterized by deviation from the mean value within ±37 mm at a confidence probability of observations of β=80%. Similarly, confidence limits for $\beta$=80% are 0.604.

Analysis of statistical processing of the results of the observations has shown that all series generally correspond to the normal distribution, which is determined by the ratio of symmetry indicators and kurtosis to their average errors. These ratios are determined within the limits of permissible deviations, and therefore, asymmetry and kurtosis, in this case, do not matter significantly.

Simultaneously, studies of the operability of skidding tracks reinforced by felling residues were carried out according to the scheme presented in Figure 4. At that, we checked the operability of the wheel track of the failed portage (Figures 4a and 4b), reinforced before starting the tests (Figure 4b).

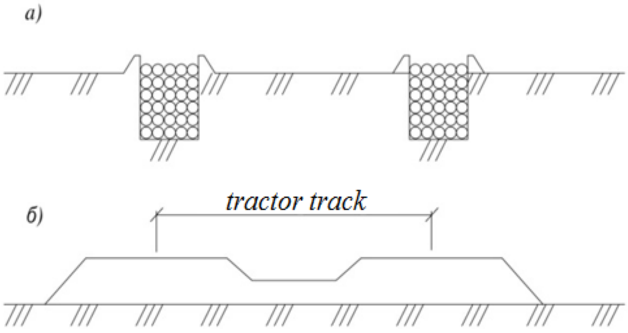

**Fig. 4: Schemes for strengthening skidding tracks: a) strengthening the track of a failed portage (longitudinal laying of felling residues); b) strengthening the portage with the transverse laying of felling residues**

## III. CONCLUSION

Comparative tests of tracked and wheeled tractors when moving along a reinforced track have shown that a reinforced track, when moving a wheeled tractor, can withstand a significantly greater number of passes than when moving a tracked tractor. Tests have shown that a wheeled tractor, when moving at a speed of 8.6 km/h with a bundle of 3 $m^3$, can carry out 200 passes after repair. Because by the 200th pass of the tractor, the entire cut-over land, necessary for U-turns and entry to the studied portage turned out to be broken, while its continuous strengthening became impossible, after the 200th pass, tests on this portage were stopped, although the portage allowed the tractor to move along it for a large number of times. Before the 9th passage, the branches were compacted and tied with liquid soil, after which there were no changes in portage characteristics. At that, respectively, 180 and 240 passes were performed with bundles of 2.25 and 1.75 $m^3$. The nature of the change in the portage condition with a reinforced track remained the same as when moving a tractor with a bundle of 3 $m^3$. Comparative tests of a caterpillar tractor have shown that already on the 1st -2nd passes, tree branches started to break, while at the 3rd -5th passes, branches started to be thrown out of the track intensively.

Observations of the movement of a wheeled tractor with a bundle of 3 $m^3$ along a reinforced portage had shown that before the 5th pass, the tree branches were compacted and pressed into the upper waterlogged soil layer with their slow destruction, and from the 10th pass, compaction of the upper soil layer by wheels and the dragging part of branch bundles destroyed the reinforcement and formation of a track in some places. On the 14th pass, intense destruction of branches began along the entire length of the portage, and the track in the reinforcing layer of branches was becoming visible. Then, until about 20th passes, intense breaking of branches was noted, while at 21st-24th passes were characterized by complete rupture of the soil layer reinforced by branches, and the depth of the formed track reached 15 cm.

After the 24th passes, due to the complete rupture of the reinforced layer, the formation of a track was identical to moving along an unreinforced portage.

When moving along the reinforced portage of a wheeled tractor with a bundle of 2.25 and 1.75 $m^3$, it was revealed that forming a track in the reinforced layer of branches ends after 16th and 19th passes, respectively, and a complete rupture of the reinforced layer of branches occurred after 27th and 36th pass of the tractor.

For comparison, a caterpillar tractor was also used in this experiment. With a load of 3 $m^3$, the following was observed: for 1-2 passes, the tree branches were destroyed and pressed into the soil, then up to 7th pass, the branches were thrown with earth, and from 8th pass, in some areas, a track began to form in the reinforced layer. Starting from the 14th pass, intense forming of the wheel track took place along the entire length of the portage in the reinforced layer of branches, and this process of track formation with the reinforcement of branches continued until the 28th pass. At that, the depth of the track at some places reached 25 cm. After 30th-31st passes, the same process of throwing branches out of the track was observed, similarly as when moving a wheel tractor along a reinforced track. A tractor passes with a bundle of 2.25 $m^3$ have shown that the destruction process of the reinforced layer of branches occurred almost in the same way as for a load of 3 $m^3$. Finally, the track in the reinforced layer was completely formed after 17 passes, and the throwing of branches from the track did not occur until 30-33 passes. With a load of 1.75 $m^3$, the track in the reinforced layer was completely formed also after 17 passes and the throwing of branches – after 33 passes.

## REFERENCES

[1] A.N.Belyaev, V.G.Kozlov, I.A.Vysotskaya, T.V. Trishina, Computation of vehicle motion path upon entering a turn, International Journal of Engineering and Advanced Technology, 1 (2019) 4527-4531.

[2] E. V. Kondrashova, T. V. Skvortsova, Sovershenstvovanieorganizatsiidorozhnogodvizheniya v transport nykh sistemakhlesnogo kompleksa [Improvement of traffic arrangement in transport systems of timber complex], Sistemy upravleniyaiin formats ionnyetekhnologii, 3.2(33) (2008) 272–275.

[3] V. G. Kozlov, Methods, models, and design algorithms of wood transportation roads with consideration for the influence of climate and weather on traffic conditions, PhD thesis, Arkhangel'sk: SAFU, (2017).

[4] V. G. Kozlov, A. V. Skrypnikov, E. V. Chernyshova, E. V. Chirkov, S. A. Postavnichij, R. V. Mogutnov, Teoreticheskieosnovyimetodymatematicheskogomodelirovaniyale sovoznyhavtomobil'nyhdorog. Izvestiya vysshihuchebnyhzavedenij, Lesnojzhurnal, 6 (2018) 117-127.

[5] V. G. Kozlov, A. V. Skrypnikov, E. Yu. Mikova, R. V. Mogutnov, E. V. Chirkov, Formirovaniemodeliproektirovaniyasistemy «dorozhnyeusloviya – transportnyepotoki» iputieerealizatsii [Design model of "road conditions – transport flow" system and its implementation], Lesoinzhenernoedelo, 8(1) (29) (2018) 100–111. DOI: 10.12737/article_5ab0dfbe6ece23.91630316

[6] V. G. Kozlov, A. V. Skrypnikov, E. Yu. Mikova, R. V. Mogutnov, Yu. A. Zelikova,

Kompleksnyeeksperimental'nyeissledovaniyaizmeneniyaparametrovikharakteristikdorozhnykhuslovii, transportnykhpotokovirezhimovdvizheniya pod vliyaniemklimataipogody [Comprehensive experimental studies of parameters and properties of road conditions, transport flows and traffic modes under the influence of climate and weather], Lesotekhnicheskiizhurnal, vol. 8, no. 2(30), (2018) 156–168. DOI: 10.12737/article_5b240611858af4.37544962

[7] V. G. Kozlov, A. V. Skrypnikov, S. I. Sushkov, I. N. Kruchinin, I. V. Grigorev, A. A. Nikiforov, Y. N. Pilnik, A. V. Teppoev, M.Lavrov, O. M. Timokhova, Enhancing quality of road pavements through adhesion improvement, Journal of the Balkan Tribological Association, 3 (2019) 678-694.

[8] B. V. Labudin, V. R. Ivko, E. I. Koltsova, A. V. Skrypnikov, V. G. Kozlov, D. M. Levushkin, M. V. Matsnev, V. A. Zelikov, Increasing pit road inclinations at high latitude deposits of solid minerals, ARPN Journal of Engineering and Applied Sciences, 15(19) (2020) 2168-2173.

[9] O. V. Ryabova, A. V. Skrypnikov, V. G. Kozlov, P. V. Tikhomirov, Studying a geographical environment for road design, Russian Journal of Building Construction and Architecture, 1(49) (2021) 66-78.

[10] V. V. Sil'yanov, Yu. M. Sitnikov, Raschetskorosteidvizheniyapriproektirovaniiavtomobil'nykhdorog [Prediction of traffic velocities upon designing of motor roads], MADI, 72 (1974) 47–66.

[11] D. L. Drew, Traffic Flow Theory & Control, McGraw Hill, 1964.

[12] V.N.Ivanov, V.N. Erokhov, Vliyanieparametrovavtomobil'nykhdorognaraskhodtopliva [The influence of motor road parameters on fuel consumption],Avtomobil'nyedorogi, 8 (2014) 10–13.

[13] Ya.A.Kaluzhskii, I.V.Begma, V.M.Kislyakov, V.V. Filippov, Primenenieteoriimassovogoobsluzhivaniya v proektirovaniiavtomobil'nykhdorog [Theory of queuing in the design of motor roads], Transport, Moscow, (1969).

[14] Ya.V. Khomyak, Proektirovanieseteiavtomobil'nykhdorog [Designing of motor road networks], Transport, Moscow, (1983).

[15] E.V. Chernyshova, Metodyformirovaniyatsifrovoimodelimestnostipritrassirovaniilesovoznykhavtomobil'nykhdorog [Formation of digital model of terrain upon location of wood transportation roads],Sistemy. Metody. Tekhnologii, 3(35) (2017) 143–148.

[16] E. V. Chernyshova, Algoritmresheniyazadachioptimal'nogotrassirovaniyalesovoznoiavtomobil'noidoroginaneodnorodnoimestnosti [Solution algorithm of the problem of the optimum location of wood transportation road on composite terrain], Vestnik VGUIT, vol. 79, no. 2(72) (2017) 113–120.

[17] V.F. Babkov, Dorozhnyeusloviyaibezopasnost' dvizheniya [Road conditions and traffic safety], Transport, Moscow, (1993).

[18] A.K.Birulya, Ekspluatatsiyaavtomobil'nykhdorog [Motor road maintenance], Transport, Moscow, (1966).